

The braking index of PSR J1734–3333 and the magnetar population

C. M. Espinoza

Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, UK

cme@jb.man.ac.uk

A. G. Lyne

Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, UK

M. Kramer

MPI für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

R. N. Manchester

Australia Telescope National Facility, CSIRO Astronomy and Space Science, PO Box 76, Epping NSW 1710, Australia

and

V. M. Kaspi

Department of Physics, McGill University, 3600 University Street, Montreal, QC H3A 2T8, Canada

ABSTRACT

PSR J1734–3333 is a radio pulsar rotating with a period $P = 1.17$ s and slowing down with a period derivative $\dot{P} = 2.28 \times 10^{-12}$, the third largest among rotation-powered pulsars. These properties are midway between those of normal rotation-powered pulsars and magnetars, two populations of neutron stars that are notably different in their emission properties. Here we report on the measurement of the second period derivative of the rotation of PSR J1734–3333 and calculate a braking index $n = 0.9 \pm 0.2$. This value is well below 3, the value expected for an electromagnetic braking due to a constant magnetic dipole, and indicates that this pulsar may soon have the rotational properties of a magnetar.

While there are several mechanisms which could lead to such a low braking index, we discuss this observation, together with the properties exhibited by some other high- \dot{P} rotation-powered pulsars, and interpret it as evidence of a possible evolutionary route for magnetars through a radio-pulsar phase, supporting a unified description of the two classes of object.

Subject headings: pulsars: general — pulsars: individual (PSR J1734–3333) — stars: neutron

1. Introduction

Radio pulsars and magnetars are believed to be neutron stars which have been formed in the collapse of the cores of massive stars in supernova explosions (Pacini 1967; Duncan & Thompson 1992). Despite this common origin, they have very different rotational and radiative properties (Woods & Thompson 2006; Mereghetti 2008). While radio pulsars generally rotate with periods P of 0.01–1 second and exhibit no remarkable X-ray emission, magnetars have periods ranging from 2–12 seconds and are generally intense sources of X-rays, sporadically undergoing outburst episodes.

The original theory of magnetars (Duncan & Thompson 1992) suggested that some neutron stars evolve under different circumstances to normal, or rotation-powered, radio pulsars. Convection and fast rotation in their early stages would quickly generate strong magnetic fields, ultimately producing Soft Gamma Repeaters (SGRs) and Anomalous X-ray pulsars (AXPs), the two manifestations of magnetars (Woods & Thompson 2006). Decay of their extremely-high magnetic field is believed to be the key to explaining outburst episodes and the excess of X-ray luminosity over their rate of loss of rotational energy (Thompson & Duncan 1995; Woods & Thompson 2006; Mereghetti 2008).

However, it is not clear whether they are indeed born with different properties or whether there is an evolutionary relationship between the two species (Lyne 2004; Kaspi & McLaughlin 2005; Gavril et al. 2008; Hales et al. 2009). The discovery of radio pulsars with rotational properties approaching those of magnetars and the existence of objects of both types having some similar emission properties is now well established (Kramer et al. 2007; Gavril et al. 2008; Camilo et al. 2008; Levin et al. 2010). We have carried out timing observations of one of these intermediate objects, PSR J1734–3333, in order to study its rotational evolution. In this letter we present the measurement of the braking index of this pulsar, a most unusual value which defies the standard models for pulsar spin-down.

1.1. Braking index and movement on the $P - \dot{P}$ diagram

The rotational relationship between radio pulsars and magnetars is best demonstrated in the period – period-time-derivative ($P - \dot{P}$) diagram (Fig. 1). Radio pulsars are believed to be formed in the upper left region of the diagram, with short period and large slow-down rate, and move generally to the right and downwards. Magnetars have longer periods and larger slow-down rates than young radio pulsars and are found in the upper right region of the diagram. The chief rotational slow-down mechanism is often assumed to be loss of energy through electromagnetic radiation produced by a dipolar rotating neutron-star magnetic field. Thus, the position in the diagram is conventionally interpreted in terms of the constant surface dipolar magnetic field at the magnetic equator required to slow down a standard neutron star ($B_s = 3.2 \times 10^{19} \sqrt{P\dot{P}}$ G), as well as the characteristic age $\tau_c = -\nu/2\dot{\nu} = P/2\dot{P}$ of the neutron star (with $\nu = 1/P$) (e.g. Lyne & Smith 2006). According to this, magnetars have surface magnetic fields of 10^{14-15} G, about two orders of magnitude higher than those of most normal radio pulsars, and are as young as young radio pulsars (1–100 kyr).

Motion in the $P - \dot{P}$ diagram can be described by the braking index, n , defined by

$$\dot{\nu} = -k\nu^n \quad \text{or} \quad \dot{P} = kP^{2-n} \quad , \quad (1)$$

where k is a positive constant. With this definition, the slope of the evolutionary path in the diagram is equal to $2 - n$. For pure magnetic braking with a constant dipolar magnetic field we expect $n = 3$. As a result, neutron stars are expected to follow lines of constant dipolar magnetic field (Fig. 1), with a slope of -1 . However, systematic variations of the moment of inertia or magnetic field, non-dipolar braking resulting from higher-order magnetic multipoles or stellar winds could effectively change the slope of movement in the diagram (Manchester et al. 1985; Blandford & Romani 1988).

Observationally, the braking index can be determined from measurement of the first two derivatives of ν , since differentiation of the above power-law (Eq. 1) gives $n = \nu\ddot{\nu}/\dot{\nu}^2$. Unfortunately, few values of n have been determined because young pulsars are often not stable rotators and short-term timing irregularities in the form of glitches and timing noise often mask any systematic motion in the $P - \dot{P}$ diagram. However, with long observational time-baselines it is often possible to establish the underlying movement across the diagram. So far, seven pulsars have steady enough rotation that stable values of braking index have been determined (Lyne et al. 1993, 1996; Middleditch et al. 2006; Livingstone et al. 2007; Weltevrede et al. 2011) (see Table 1). These values are all less than three and hence the slope of their movement in the $P - \dot{P}$ diagram is somewhat more positive than -1 . The simple dipolar spin-down model is clearly imperfect.

2. The braking index of PSR J1734–3333

PSR J1734–3333 lies in the region between young pulsars and magnetars on the $P - \dot{P}$ diagram and is a young radio pulsar ($\tau_c = 8$ kyr), possibly associated with the supernova remnant (SNR) G354.8–0.8 (Manchester et al. 2002). It has a high inferred dipolar magnetic field (5×10^{13} G), one of the highest known values amongst rotation-powered pulsars, and similar to the lowest values amongst magnetars (even without considering the SGR with a very low \dot{P} reported by Rea et al. (2010); see Fig. 1). It was discovered during the Parkes Multibeam Pulsar Survey (Morris et al. 2002), and it has been observed regularly since August 1997 by the 64-m telescope at Parkes and the 76-m Lovell telescope at Jodrell Bank. Like other high- \dot{P} radio pulsars, PSR J1734–3333 presents modest X-ray luminosity, not surpassing its rotational spin-down energy loss rate (Olausen et al. 2010), although with somewhat higher temperature than is observed for pulsars with lower effective dipolar magnetic fields but similar characteristic age (Zhu et al. 2010). It exhibits timing noise typical of a pulsar of its age and has not glitched in 13.5 years, making possible a measurement of the $\ddot{\nu}$ due to secular slow-down.

The evolution of the timing residuals of PSR J1734–3333 relative to a simple slow-down model of the rotational frequency and first derivative is shown in Fig. 2. The curve is a fit for a second derivative as well, and these values are given in Table 2. In order to assess the errors in the parameters we have measured the spectrum of the residuals from the second-derivative fit and conducted Monte Carlo simulations by randomly varying the phases of the spectral components. Quoted uncertainties correspond to the standard deviations around the mean values. We obtain $\ddot{\nu} = 2.8 \pm 0.6 \times 10^{-24}$ Hz s^{−2}, which implies that the present braking index of this pulsar is very low, being $n = 0.9 \pm 0.2$.

Many young pulsars such as the Vela pulsar (PSR B0833–45), PSR B1800–21 and PSR B1823–13 have large positive values $\ddot{\nu}$ associated with recovery from glitches (Lyne & Smith 2006). If there has been any recent glitch activity in PSR J1734–3333, the present value of $\ddot{\nu}$ would very likely be contaminated by any such relaxation and the long-term value would be even smaller (Hobbs et al. 2010), indicating that the actual long-term braking index of PSR J1734–3333 must be less than or equal to 0.9 ± 0.2 .

3. Discussion

This braking index measurement indicates a movement in the $P - \dot{P}$ diagram with a slope $2 - n$ of at least 0.9. The inset diagram in Fig. 1 shows how, superposed on timing noise, there is a clear and systematic motion over nearly 14 years towards the top-right region

of the diagram, where magnetars are found. If this behavior is sustained, we can estimate the time it will take for the pulsar to move from its present position in the diagram to the magnetar region. Using the power law that defines the braking index (Eq. 1), an object relocates in Fig. 1 from (P_1, \dot{P}_1) to (P_2, \dot{P}_2) , where $\dot{P}_2 = \dot{P}_1(P_2/P_1)^{2-n}$, in a time given by

$$\begin{aligned} \Delta T &= \frac{2\tau_c}{n-1} \left[\left(\frac{P_2}{P_1} \right)^{n-1} - 1 \right] \quad (n \neq 1) \\ \Delta T &= 2\tau_c \ln \left(\frac{P_2}{P_1} \right) \quad (n = 1), \end{aligned} \quad (2)$$

where $\tau_c = P_1/2\dot{P}_1$ is the present characteristic age. The braking index of a neutron star is determined by the mechanism which provides the slow-down torque, due either to electromagnetic radiation or particle flow, and any variation in the moment of inertia or magnetic field (Manchester et al. 1985; Blandford & Romani 1988; Lyne & Smith 2006). If these underlying physical processes remain unchanged and PSR J1734–3333 continues to evolve with a constant braking index of $n = 0.9$, Eq. 2 implies that it would reach a period of 8 s in only 29 kyr. It would then be situated in the middle of the magnetars. The characteristic age would be 6.7 kyr, less than its present value of 8.1 kyr and much smaller than the combined durations of its previous life as a radio pulsar and its subsequent path amongst magnetars.

Assuming the relation between the neutron star magnetic field and slow-down rate given in section 1.1, the position in the P – \dot{P} diagram indicates the effective dipole magnetic field strength. Most quoted magnetic field strengths, including those of magnetars, are based upon this calculation. The upward movement on the P – \dot{P} diagram of PSR J1734–3333 then corresponds to an increase of the effective surface neutron-star dipole magnetic field. In this basic model (magnetic-dipole radiation of an orthogonal rotator in vacuum), $n < 3$ can be obtained by variations of either the moment of inertia of the star or the magnetic moment (Blandford & Romani 1988). While the moment of inertia is indeed expected to decrease in young pulsars due to re-shaping caused by the secular spin-down, it is unlikely that this process can be sustained over long times. In contrast, formation of cracks in the crust are expected, that may cause glitches or abrupt spin irregularities which would be visible in the timing residuals (Baym et al. 1969; Alpar et al. 1996). Nothing like this is visible in the data for PSR J1734–3333 during the 13.5 years of observations. Variations of the magnetic moment could be caused by alignment or misalignment of the magnetic dipole with respect to the spin axis or by increase or decrease of the magnetic field strength. To obtain $n \sim 0.9$ the magnetic axis would have to migrate away from the rotation axis with a time-scale of 10^4 yr. No such changes have ever been measured and the available evidence for secular magnetic moment migration in radio pulsars points to alignment (rather than misalignment) on time-scales of 10^{6-8} yr (Tauris & Manchester 1998; Weltevrede & Johnston 2008; Young et al. 2010). Hence, the only option in the simple magnetic-dipole radiation

scenario to produce $n < 3$ is surface magnetic field growth.

The above interpretation almost certainly involves significant simplification. Observations have shown that magnetospheric processes could exert an extra torque on the crust, perturbing the effects of pure electromagnetic braking (Kramer et al. 2006; Lyne et al. 2010). Indeed, out-flowing plasmas could remove enough angular momentum from the star to become the dominant spin-down mechanism, thereby giving $n \sim 1$. In this scenario, it has been predicted that strong relativistic winds could produce $n = 1$ (Michel 1969; Manchester et al. 1985; Alvarez & Carramiñana 2004; Bucciantini et al. 2006). We note, however, that Olausen et al. (2010) found no evidence for extended emission around PSR J1734–3333 in X-ray observations, suggesting the absence of a pulsar wind nebula (PWN).

The ideal magnetic-dipole radiation model has been modified in several occasions to produce more realistic models, commonly consisting of a corotating closed-field-line region surrounded by an open-field-line region. These models consider different dipole inclination angles and incorporate the effects of a plasma filled magnetosphere (e.g. Melatos 1997; Contopoulos & Spitkovsky 2006; Li et al. 2011). In these scenarios the spin-down can not only be regulated by the strength of the dipolar magnetic field, but importantly also by the dipole inclination angle, the spin rate of the open field lines (Contopoulos & Spitkovsky 2006), and the conductivity of the magnetosphere (Li et al. 2011). In these models, a braking index of three is still expected to be the norm, while for a braking index $n < 3$ it has to be assumed that either the co-rotating magnetosphere ends well inside the light cylinder (Contopoulos & Spitkovsky 2006) or the conductivity is increasing with time (Li et al. 2011). Both may explain the case of PSR J1734–3333, but we remark that the large majority of measured braking indices are not three as expected from these models but are smaller than three. In the case studied here, the braking index is much smaller than three, so that we also consider the alternative explanation that the dipole surface magnetic field may increase with time. It is possible, that a combination of effects contributes to the observed spin-down.

Our ignorance of the actual spin-down mechanism for PSR J1734–3333 could be partly reduced by considering the properties of other high- \dot{P} objects. The three known radio emitting magnetars exhibit unique radio emission properties, not generally observed in normal radio pulsars (Kramer et al. 2007; Camilo et al. 2008; Levin et al. 2010), which have been attributed to the presence of strong magnetic fields. Another object, PSR J1846–0258, is an X-ray pulsar that in 2006 showed magnetar-like activity after more than 6 years of normal rotation-powered pulsar behavior (Gavriil et al. 2008). The effective dipolar magnetic field of this pulsar is amongst the highest among normal pulsars and its radiative properties during the 2006 outburst, as with the three radio magnetars, have been related to the effects of a very high surface magnetic field. By studying an unusual braking index decrease observed af-

ter the 2006 event, Livingstone et al. (2011) concluded that the effects of particle wind losses (if present) are not significant in the rotation of PSR J1846–0258. Finally, Harding et al. (1999) showed (in the case of SGR 1806–20) that even though its rapid slowdown may be caused by stellar winds, a high magnetic field may still be necessary to power the typical magnetar activity.

Thus, provided that the singular properties of high- \dot{P} neutron stars, including magnetars, are effectively driven and determined by very strong magnetic fields, the movement of PSR J1734–3333 on the P – \dot{P} diagram could be simply understood as a passage to a new magnetar life caused by surface magnetic field growth. The surface magnetic field of a neutron star could increase due to outward diffusion of a stronger internal field (Muslimov & Page 1996; Geppert et al. 1999; Ho 2011). Such a field could have been buried by hypercritical accretion of material falling back just after the supernova explosion (Chevalier 1989). In the case of ohmic diffusion, this rate will depend mainly on the depth of the particular submersion, with calculations suggesting that the inner field will start emerging with typical timescales between 10^2 to 10^6 yr (Muslimov & Page 1996; Geppert et al. 1999). This is consistent with the time required for PSR J1734–3333 to reach full magnetar spin properties. It may be that the only modification required to conventional models of magnetar formation is a possible delay of perhaps 10–100 kyr in the emergence of the magnetic field. It is possible that PSR J1734–3333 has already undergone some transitory magnetar activity and by the time it reaches full magnetar rotational properties it may have developed the full radiative properties of a magnetar.

4. Conclusions

The spin evolution of PSR J1734–3333 during the last 13.5 years is consistent with a braking index $n = 0.9 \pm 0.2$, which corresponds to a systematic movement in the P – \dot{P} diagram with a slope of at least +0.9, arriving within the region of the magnetars after about 30 kyr. We discussed that secular evolution of the magnetic-dipole inclination and systematic variations of the moment of inertia are unlikely to dominate pulsar spin evolution. Also, X-ray observations of PSR J1734–3333 show no evidence for any form of PWN (Olausen et al. 2010) which, if present, would be a signature of wind activity around this pulsar that could affect its rotation leading to a braking index $n < 3$ (e.g. Bucciantini et al. 2006). Most realistic models involving electromagnetic torques predict $n \sim 3$, although could give $n < 3$ if the corotating magnetosphere is small (Contopoulos & Spitkovsky 2006) or if the magnetosphere’s conductivity is increasing with time (Li et al. 2011).

We interpret the movement of PSR J1734–3333 in the P – \dot{P} diagram, together with

the properties of other high- \dot{P} neutron stars, as evidence for a possible new genesis for at least some magnetars. Regardless of whether or not this movement corresponds to actual magnetic field growth, our interpretation has several satisfactory implications: Firstly, it has been suggested that the apparent excessively high birthrate (Keane & Kramer 2008) of all species of neutron stars over core collapse supernovae events can be explained if there is evolution between the species, as we suggest here. Secondly, many magnetars will be older than their characteristic ages suggest by 10-100 kyr. Therefore, not all magnetars will be young enough to be still surrounded by a visible SNR, consistent with the surprisingly small number of secure associations between magnetars and SNRs (Fig. 1) (Gaensler et al. 2001; Allen & Horvath 2004). Thirdly, the same physical processes that would be responsible for the development of the magnetar properties may be responsible for the effective dipolar magnetic field growth seen in the rotation-powered pulsars with measured values of braking index, which all have values of $n < 3$ (Fig. 1, Table 1). Finally, recent observations of Central Compact Objects (CCOs) in SNRs suggest that a significant number of neutron stars are born with long periods and low period derivatives (Halpern & Gotthelf 2010). Hence, young pulsars are not only found at the top-left of the diagram but also towards low \dot{P} values, populating the left hand side of the main bulk of pulsars and probably being progenitors for most normal pulsars. This may imply that the high- \dot{P} young pulsar population are not the progenitors of most pulsars, making feasible their possible evolution into magnetars. In summary, we suggest that, with a range of internal magnetic fields, submersion depths and initial spin periods, we could explain the existence of magnetars, CCOs and the whole radio pulsar population as one single family (cf. Kaspi 2010).

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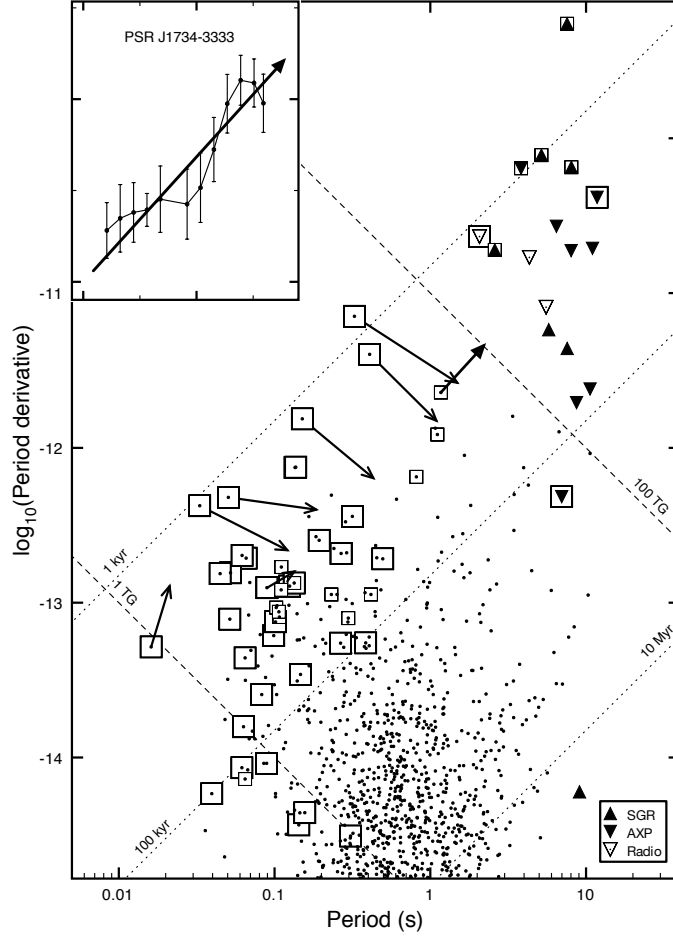


Fig. 1.— P – \dot{P} diagram for all known magnetars and young pulsars having $\dot{P} > 1.65 \times 10^{-15}$. Lines of constant magnetic field are dashed and lines of constant characteristic age are dotted, with a slope of 1. Open arrows indicate the motion of those pulsars with published values of braking index (Table 1). Each arrow represents the projected motion of the pulsar during the next 10,000 yr (excepting the one for PSR J0537–6910, for which only 2,000 yr was used), assuming that it evolves with a constant braking index n . Equal logarithmic scales are chosen, so that a pulsar will move with a slope of $2-n$. The motion of PSR J1734–3333 is represented by a closed arrow. Objects which have robust proposed associations with supernova remnants or pulsar wind nebulae are identified with a surrounding large square, with smaller squares for less convincing associations. White triangles are used for the radio emitting magnetars. The \dot{P} value of the SGR with the lowest \dot{P} corresponds to an upper limit (Rea et al. 2010). Inset: the pulsar’s motion in P – \dot{P} space over a 13.5-year period using equal logarithmic scales, but magnified by a factor of 4,000. Major ticks are separated by 5×10^{-4} s on the horizontal axis, and by 3×10^{-4} on the vertical axis. Each data point in the inset is the result of a fit of P and \dot{P} to a 1500-day interval set of times of arrival. The error bars are the standard deviations (See section 2). Most of the information was taken from the ATNF pulsar catalogue (version 1.39, <http://www.atnf.csiro.au/research/pulsar/psrcat/>), or the McGill SGR/AXP Online Catalog as it was in November 2010 (<http://www.physics.mcgill.ca/~pulsar/magnetar/main.html>).

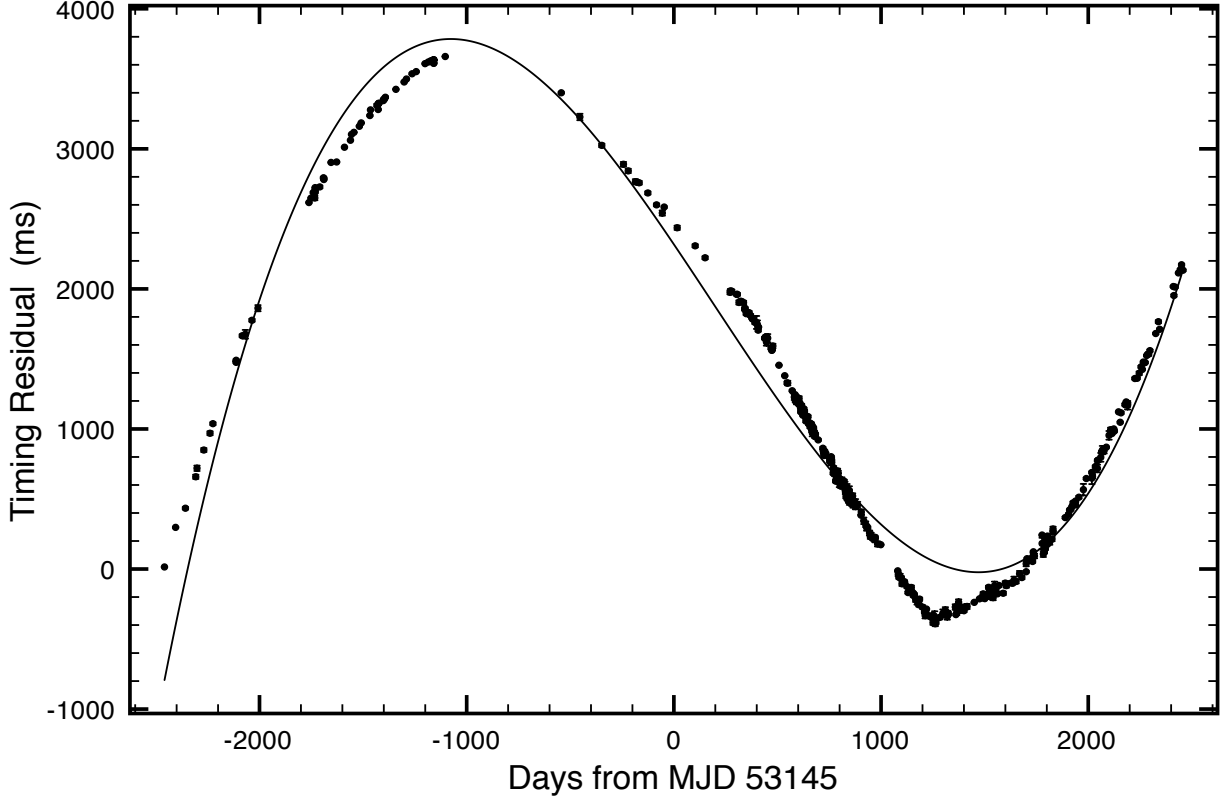


Fig. 2.— Timing residuals of PSR J1734–3333 over a 13.5-year interval. The timing residuals are the difference between the observed times of arrival of pulses and those predicted by a simple slow-down model of frequency and first derivative $\dot{\nu}$. The curve shows the slow-down model after including the fitted value of frequency second derivative of $2.8 \pm 0.6 \times 10^{-24} \text{ Hz s}^{-2}$ (Table 2), corresponding to a braking index of $n = 0.9 \pm 0.2$.

Table 1. Published braking indices.

| Pulsar | n | Reference |
|------------|----------|---------------------------|
| B0531+21 | 2.51(1) | Lyne et al. (1993) |
| J0537–6910 | –1.5 | Middleditch et al. (2006) |
| B0540–69 | 2.140(9) | Livingstone et al. (2007) |
| B0833–45 | 1.4(2) | Lyne et al. (1996) |
| J1119–6127 | 2.91(5) | Weltevrede et al. (2011) |
| B1509–58 | 2.839(1) | Livingstone et al. (2007) |
| J1846–0258 | 2.65(1) | Livingstone et al. (2007) |
| J1734–3333 | 0.9(2) | this work |

Note. — The uncertainty in the last shown digit is quoted in parenthesis. While all other values come from phase-coherent timing, the values for PSR B0833–45 and PSR J0537–6910 were obtained by studying the evolution of the spin-down rate after several glitches. The braking index for this last pulsar was calculated from a rough estimate of the systematic variation during more than 8 yr of the frequency derivative data. We note that the braking index of PSR 1846–0258 was found to be 2.2 ± 0.1 when using data following the 2006 event (see section 2) (Livingstone et al. 2011).

Table 2. Observed and derived parameters for PSR J1734–3333 obtained from fits to the pulse times-of-arrival.

| Parameter | Value |
|--|----------------|
| RAJ | 17:34:26.9(2) |
| DECJ | −33:33:20(10) |
| ν (Hz) | 0.855182765(3) |
| $\dot{\nu}$ (10^{-15} Hz s $^{-1}$) | −1667.02(3) |
| $\ddot{\nu}$ (10^{-24} Hz s $^{-2}$) | 2.8(6) |
| P (s) | 1.169340684(4) |
| \dot{P} (10^{-15}) | 2279.41(4) |
| \ddot{P} (10^{-24} s $^{-1}$) | 5.0(8) |
| Timing Epoch (MJD) | 53145 |
| Data span (MJD) | 50686–55602 |
| DM (cm $^{-3}$ pc) | 578(9) |
| S ₁₄₀₀ (mJy) | 0.5 |
| W ₅₀ (ms) | 500 |
| Distance (kpc) | 7.4 |
| Characteristic Age (kyr) | 8.1 |
| Surface magnetic field (TG) | 52 |
| Braking Index, n | 0.9(2) |

Note. — Standard errors are given in parenthesis in units of the last quoted digit. See section 2 for more details.